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Naghma Hall

APPLICATION FOR UNITED STATES LETTERS PATENT

FOR

APPARATUS AND METHODS FOR MONITORING PIPELINES

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CROSS-REFERENCE TO RELATED APPLICATIONS

The present application is a Continuation-in-Part of United States Patent Application 10/421,475 filed on April 23, 2003, which is incorporated herein by reference.

BACKGROUND OF THE INVENTION

Field of the Invention

This invention relates to monitoring of flow conduits, such as a gas pipelines, and more particularly to an articulated mobile sensing and interrogation device for measuring parameters of interest of the flow conduit and remotely interrogating sensors attached to the pipeline.

Description of the Related Art

Fluid conduits such as pipelines and aqueducts extend for tens, hundreds, or thousands of kilometers and may be used to transport liquids, gases, slurries or combinations thereof. Such conduits may have multiple sections that run above or below ground. Sections may be run underground to avoid natural obstacles such as rivers or simply as a safety precaution. Other sections may be run above ground depending on the topography and underlying strata. Sensing stations are commonly located at major features, such as pumping station that may be separated by tens or hundreds of kilometers. Sensors are used to determine any of a number of parameters of interest related to the operation and safety of the conduit and/or related to the fluid transported therein. However, due to the relatively large separation of these stations, conditions that may be indicative of potential problems or

failures may go undetected until they become so great as to cause a catastrophic event, such as for example a substantial leak that may be a serious environmental problem. It would be highly desirable to be able to determine various parameters relating to the physical condition of the conduit including, but not limited to, mechanical strain and stress, crack initiation and propagation, temperature, acceleration and vibration, seismic events, corrosion, pressure integrity, and flowing fluid properties, such as chemical species, radiation, and chemical contamination. The very nature of the length and location of such conduits, however, make the distribution of power and signal lines to multiple measurement stations substantially impractical and cost prohibitive.

Mobile devices, commonly called pigs, may be moved through a pipeline by the fluid pressure within the pipeline to provide information regarding the condition of the pipeline. The device can perform any number of tasks that can vary between simple tasks, such as cleaning pipelines, to more sophisticated tasks such as measurement of metal loss of the pipe due to corrosion, cracks, deformation and the like. Pigs that perform these tasks are called "smart pigs". Smart pigs may consist of various modules, in which one of the modules commonly performs the function of propelling the smart pig through the pipeline. Such devices can have on-board devices for sensing a limited range of parameters of interest about the pipeline as the mobile device passes through the pipeline. Typically such devices detect parameters related to wear and corrosion, such as pipe diameter and/or magnetic flux leakage (MFL). Actual in situ physical parameters of the pipeline, such as those described previously, require sensors physically attached to the pipeline. Such sensors should preferably be self-contained such that they do not require electrical connections via cables. An example of such

self-contained sensors is disclosed in U.S. Patent Application No. 10/421,475 filed on April 23, 2003, previously incorporated herein by reference. Other parameters and tests may also be required to be carried out by the mobile device.

There is a demonstrated need, therefore, for a mobile device capable of performing tests along a pipeline as well as interrogating remote sensors attached to the pipeline.

SUMMARY OF THE INVENTION

The present invention contemplates a system including a mobile interrogation device for traversing a pipeline and monitoring various parameters related to the integrity of the pipeline.

In one preferred embodiment, a system for monitoring at least one parameter of interest relating to a pipeline having a fluid flow therein, comprises at least one measurement station coupled to the pipeline for taking a measurement relating to the parameter of interest. A flow propelled interrogation device is adapted to move proximate the measurement station. The interrogation device is further adapted to transmit a first signal to the measurement station and to receive a second signal from the measurement station relating to the parameter of interest.

In one aspect, a method for monitoring at least one parameter of interest relating to a pipeline having a fluid flow therein, comprises coupling at least one measurement station to the pipeline at a predetermined location. The measurement station is adapted to measure the at least one parameter of interest. A flow propelled interrogation device is passed proximate the at least one measurement station. A first signal is transmitted from the interrogation

device to the measurement station, with the measurement station measuring the at least one parameter of interest in response thereto. The flow propelled interrogation device receives a second signal related to the parameter of interest transmitted by said measurement station.

In another aspect, an interrogation device for determining at least one parameter of interest relating to a gas pipeline, comprises at least one housing having a plurality of wheel assemblies mounted thereon,. The wheel assemblies are extendable to contact an inner wall of the pipeline. A sail is engaged with the housing for intercepting at least a portion of the fluid flow for propelling the interrogation device along the pipeline. A controller controls the motion of the interrogation device. The controller also transmits at least one first signal to and receives at least one second signal from at least one measurement station attached to the pipeline. A power source supplies power to the controller.

In yet another aspect, a method for determining at least one parameter of interest related to a pipeline having a gas flowing therethrough, comprises traversing an interrogation device through the pipeline. The interrogation device is adapted to provide a predetermined pressure disturbance for inducing a predetermined strain in the pipeline. A first signal is transmitted from the interrogation device to each of the plurality of measurement stations as the interrogation device moves proximate each of said plurality of measurement stations. The measurement station measures the at least one parameter of interest in response to the first signal. The interrogation device receives a second signal related to the parameter of interest transmitted by the measurement station.

BRIEF DESCRIPTION OF THE DRAWINGS

For detailed understanding of the present invention, references should be made to the following detailed description of the preferred embodiment, taken in conjunction with the accompanying drawings, in which like elements have been given like numerals, wherein:

Figure 1 is a schematic drawing of a fluid conduit traversing an uneven terrain;

Figure 2 is a schematic drawing of a self contained measurement and information station according to one embodiment of the present invention;

Figure 3 is a schematic drawing of a measurement module of a self contained measurement and information station according to one embodiment of the present invention;

Figure 4 is a schematic drawing of an articulated conduit inspection pig for use as a mobile interrogation device according to one embodiment of the present invention;

Figure 5 is a schematic drawing showing an automotive device and an aircraft device for use as mobile interrogation devices according to one embodiment of the present invention;

Figure 6 is a schematic drawing of a composite conduit with embedded conductors for transmitting command signals and/or power to multiple measurement stations according to one embodiment of the present invention;

Figure 7 is a schematic drawing of a coiled composite tubing having embedded conductors and a plurality of self contained measurement and information stations disposed along the tubing according to one embodiment of the present invention;

Figure 8 is a schematic drawing of a casing with a plurality of self contained measurement and information stations disposed along the tubing and an interrogation device deployed on a tubular member according to one embodiment of the present invention;

Figure 9A is a schematic drawing of an interrogation vehicle traversing a pipeline according to one embodiment of the present invention;

Figure 9B is a schematic drawing showing View A-A depicted in Figure 9A; and

Figure 9C is a schematic drawing showing a pressure profile in a pipeline caused by the movement of an interrogation device through the pipeline according to one embodiment of the present invention.

DESCRIPTION OF PREFERRED EMBODIMENTS

In one preferred embodiment, see **Figure 1**, a fluid conduit **1** extends across terrain **10**. Note that the term fluid conduit as used herein, means a closed conduit, such as a pipeline or other substantially tubular member, and an open conduit such as an aqueduct for transporting liquids such as water. Such conduits may extend for tens, hundreds, or thousands of kilometers and may be used to transport liquids, gases, slurries or other fluids. The conduit **1,** for example may be a pipeline having multiple sections **5, 6, 7** that run above or below ground. Sections may be run underground to avoid natural obstacles such as river **8** or simply as a safety precaution. Other sections may be run above ground depending on the topography and underlying strata. Self contained measurement and information stations **20**, called measurement stations for simplicity, are disposed along conduit **1** at predetermined locations, to determine any of a number of parameters of interest related to the operation and safety of the conduit and/or related to the fluid transported therein. The greater the number of measurement stations **20**, the better will be the confidence that the conduit is operating properly. Various parameters may be measured relating to various physical conditions including, but not limited to, mechanical strain and stress, crack initiation and propagation, temperature, acceleration and vibration, seismic events, corrosion, pressure integrity, and flowing fluid properties, such as flow rate and chemical species, radiation, and chemical contamination. For an open channel, such as an aqueduct, measurement stations **20** may be mounted to determine parameters related to the flow channel such as, for example, seismic events, and/or for determining parameters related to the flowing fluid. Such fluid related parameters, for a water supply flow for example, may relate to chemical analysis and water

purity or to contamination by chemical and/or biological agents. The very nature of the length and location of such conduits make the distribution of power and signal lines to multiple measurement stations **20** physically impractical and cost prohibitive.

Figures 2 shows one preferred embodiment of measurement station **20** having measurement module **30**, radio frequency (RF) transmitting and receiving antenna **22**, and flexible adhesive base **21** for attaching measurement module **30** to flow conduit **1**. In one embodiment, see **Figure 3**, measurement module **30** includes at least one sensor **27** for detecting the parameter of interest. Alternatively, sensor **27** may be external to measurement module **30** and suitably electrically connected using techniques known in the art. Interface module **24** conditions the output signal from sensor **27**, if necessary, and transfers the signal to data memory in controller module **23**. Controller module **23** has a processor with sufficient memory for storing program instructions and for storing acquired sensor measurement data. The controller module may contain a unique identification, such as a digital identifier, for uniquely identifying each measurement station **20** that may be used for correlating the measurements with location on the conduit **1**. Also included is RF transceiver **26** for receiving command and power signals and for transmitting data signals in response to the received command signals.

In one preferred embodiment, the measurement module **30** has no internal power source, but receives power via the received RF signal. This power is converted to usable power by power module **28**. Sensor **27** is chosen as a low power sensor such that the RF link transmits sufficient power to power measurement module **30** including sensor **27** and to transmit the resulting data signal using RF transceiver **26**. The components of measurement

module **30** are encapsulated in a suitable compound **29** to protect the components from the environment.

The RF command signal and RF power are transmitted from, and the data signals received by, a mobile interrogation device (see **Figures 4 and 5**) such as an internal inspection pig **40**, an automotive device **45**, and an aircraft device **50**. Inspection pigs are commonly self-powered for movement in the conduit or , alternatively, may be pumped through flow conduit **1**. Any type of inspection pig is suitable for this invention The automotive device **45** may be any common vehicle including, but not limited to an automobile, a truck, and an all-terrain vehicle. The automotive device, is adapted to carry an RF transceiver (not shown) and a controller (not shown) transmitting command signals and power to measurement stations **20** and receiving and storing data signals from measurement stations **20**. The aircraft device **50** may be an airplane, helicopter, or any suitable aircraft and may be manned or a remotely controlled, unpiloted aircraft. Remotely controlled aircraft device **50** may be preprogrammed to follow a predetermined flight pattern along the known path of flow conduit **1**, using, for example, preprogrammed way points and GPS signals to guide aircraft device **50** along the predetermined flight pattern. Relatively small remotely controlled vehicles are commercially available.

The placement of a particular measurement station **20** at a predetermined location and the type of flow conduit **1** will be used to determine the type of interrogation device used for that particular measurement station **20**. For example, the flow conduit **1** may be (i) a tubular conduit of metallic material such as steel, (ii) a tubular conduit out of a non-metallic material such as a composite material, or (iii) an open-channel conduit. For a metallic conduit, the RF

energy will not penetrate the conduit. Therefore, a measurement station **20** mounted inside the metallic conduit **1** (see **Figure 4**) requires an internal interrogation device such as a pipeline pig **40**. A measurement station **20** mounted outside of a metallic conduit 1 (see **Figure 5**) requires an external interrogation device such as automotive device **45** and/or aircraft device **50**. For a composite material, the conduit **1** is substantially transparent to RF energy and allows the measurement stations **20** to be mounted internally, externally, and/or embedded within the conduit and be able to operate with an internal and/or external interrogation device.

The sensors **27** used to detect the parameters of interest include, but are not limited to, (i) mechanical strain gages, (ii) fiber optic strain gages, (iii) ultrasonic detectors for detecting micro-crack initiation and propagation , (iv) accelerometers, (v) temperature sensors, including distributed fiber optic temperature sensors known in the art, (vi) pressure sensors, (vii) corrosion detectors, (viii) radiation detectors, (ix) spectroscopic chemical detectors, and (x) ultrasonic detectors for measuring the wall thickness of the flow conduit for detecting erosion and/or corrosion of the conduit. The sensors **27** may detect characteristics associated with the conduit and/or the fluid flowing therein. One skilled in the art will recognize that many of the sensors, for example accelerometers and seismic detectors, are currently achievable using Micro Electromechanical Systems (MEMS) fabrication techniques for providing low power consumption devices. Other sensors are available using piezoelectric crystal technology or resonant crystal technology that require very low power consumption. Thermocouple temperature sensors, for example, generate their own electrical signal and do not require external power to operate.

In operation, the measurement stations **20** are disposed along the flow conduit **1**. The measurement stations **20** may be both above and below ground along the length of flow conduit **1** depending on the path of conduit **1**. An interrogation device is caused to pass in relative proximity to the measurement stations **20**. The interrogation device has an RF transceiver for transmitting command signals and power to the measurement stations **20** and for receiving data signals from the measurement stations **20**. The data collected is downloaded from the interrogation device , using techniques known in the art, to a central control station (not shown) for monitoring the various parameter data collected.

In another preferred embodiment, measurement module **30** includes an internal power source (not shown) for powering the electronic devices and sensors as required. The internal power source may include, but is not limited to, (i) a commercially packaged battery, (ii) a thick film battery integrally attached to the measurement module, (iii) a piezoelectric power source deriving power from shock and vibration in the proximity of the measurement module, (iv) a solar cell integrated into an external surface of the measurement module, and (v) a thermoelectric generator integrated into the measurement module. All of these power sources are known in the art. Any combination of these sources may be used and their selection is application specific, and may be determined without undue experimentation, by considering such factors as (i) power required for the type of sensors, (ii) transmission strength required of data signals, and (iii) location of measurement station and flow conduit (for example, above ground or below ground).

In another preferred embodiment, the power sources described above are mounted external to the measurement module **30** and connected to the measurement module via connectors and/or cables using techniques known in the art.

In one preferred embodiment, measurement module 30 contains a real time clock for time stamping measurements. A low power seismic detector, for example, may be continuously measuring seismic activity, but the data is only stored and time stamped if the sensed event exceeds a predetermined threshold or alarm criterion. The data is retrieved by the interrogation device and may be used to indicate that more extensive inspection is needed in the area where the seismic event was detected.

In one preferred embodiment, shown in **Figure 6**, composite fluid conduit **60** has electrical conductors **61** embedded in the wall **63** of fluid conduit **60** during the manufacturing process for forming the conduit. Measurement stations **20** are disposed along the conduit at at least one of (i) on an internal walls of conduit **60**, (ii) on an external wall of conduit **60** , and (iii) embedded in a wall **63** of conduit **60**. The electrical conductors **61** may be disposed substantially longitudinally in the wall of conduit **60**. Alternatively, the electrical conductors **61** may be spirally wrapped in the wall of conduit **60**. Electrical conductors **60** are connected to RF transceiver (not shown) in a controller **62**. Power and command signals are transmitted through the conductors which act as RF antennas. The signals are detected by the measurement modules 30 along the conduit. The measurement stations **20** receive and convert the RF signals to power and command instructions for taking data from sensors in the measurement modules **30**. The data are then transmitted via an RF signal that is received by the electrical conductors **61** and decoded by controller **62**, according to programmed

instructions. The signals from measurement stations **20** are suitably encoded and identified, using techniques known in the art, so as to be able to determine the measurement stations **20** associated with each data signal.

In one preferred embodiment, see **Figure 7**, a composite conduit, as described previously having embedded electrical conductors and internal, external, and/or embedded measurement stations **20**, may be formed as a coiled tubing **71** for use in drilling and/or completing a wellbore **72**. Measurements from measurement modules **30**, embedded in the coiled tubing **71**, may be used to determine parameters of interest regarding the condition of the tubing string and/or parameters related to the drilling process. Such parameters of interest include, but are not limited to, (i) directional parameters, (ii) drilling induce vibration, including axial and torsional, (iii) weight on bit, (iv) downhole pressure, (v) downhole temperature, and (vi) formation parameters including natural gamma ray emission.

In one preferred embodiment, see **Figure 8**, metallic casing **83** is fixed in place in production wellbore **80**. Measurement modules **30** are fixed to an internal surface of casing **83** and measure parameters of interest including, but not limited to, (i) fluid pressure, (ii) fluid temperature, (iii) fluid flow rate, (iv) corrosion, and (v) casing stress. An interrogation device **82** is deployed on wireline **81** and is passed in proximity to measurement modules **30** and has an RF transceiver that transmits RF power and command signals to measurement modules **30**, which in turn, make measurements and transmit that data via RF transmission to interrogation device **82**. Interrogation device **82** has internal memory for storing the received data and is downloaded at the surface. Alternatively, wireline **81** has electrical conductors

and received data is transmitted directly to the surface. The interrogation device **82** may alternatively be deployed on a coiled tubing (not shown) using techniques known in the art.

In another preferred embodiment, see **Figures 9A-9C**, a vehicle such as interrogation device **86** is adapted to traverse gas pipeline **90**. Interrogation device **86** includes sail **92** for intercepting a portion of the flowing gas **96** which acts to provide motive force and propel interrogation device **86** along pipeline **90**. Interrogation device **86** has multiple body sections, also called housings, **94** pinned together by pin **95** allowing device **86** to pivot and more easily traverse bends in pipeline **90**. Body sections **94** have multiple wheel assemblies **105** disposed substantially symmetrically around body section **94**. Preferably there are three wheel assemblies disposed around each body section. Each wheel assembly **105** includes a wheel **97** attached to an extendable arm **98**. Each extendable arm **98** is individually extendable to force wheel **97** into contact with the inner wall **106** of pipeline **90**. Extendable arms **98** may be electromechanically operated or hydraulically operated. Brake **87** is attached to at least one wheel assembly **105**. Brake **87** may be actuated electromechanically and/or hydraulically to control the speed of interrogation device **86** along pipeline **90**. Wheel assembly **105** has a rotational sensor (not shown) for determining the rotational speed of wheel **97**. Such rotational information may be used by the controller to determine speed of interrogation device **86** as well as distance traveled along pipeline **90**. Controller **107** also contains an realtime clock for time-stamping received transmissions from measurement stations **91**.

Body sections **94** have a through passage **88** allowing a portion of flow **96** to pass through and actuate a power system, such as turbine-generator **109,** positioned in flow

passage **88**. Flow **96** rotates impeller **99** which is operationally coupled to electrical generator **100** for generating electrical power usable in interrogation device **86**. Impeller **99** may also be operationally coupled to a hydraulic pump for supplying hydraulic power to interrogation device **86**. Alternatively, interrogation device **86** may be powered by batteries (not shown) carried in interrogation device **86**. Electrical generator **100** supplies power to controller **107** via wires (not shown). Controller **107** includes a processor with memory for storing program instructions and for storing measured data. Controller **107** includes circuits for interfacing with and controlling brake **87** and sail **92** for controlling the speed of interrogation device **86** according to programmed instructions. Controller **107** also includes a radio frequency (RF) transceiver for transmitting and receiving signals from measurement stations **91** disposed on inner wall **106** of pipeline **90**. Measurement stations **91** have substantially the same features and capabilities as those described previously with regard to **Figures 1-6**.

In one preferred embodiment, measurement station **91** obtains operational power from RF signals transmitted by controller **107**. Alternatively, measurement station **91** may contain an internal power source including but not limited to (i) a commercially packaged battery, (ii) a thick film battery integrally attached to the measurement module, (iii) a piezoelectric power source deriving power from vibration and/or flow energy in the proximity of the measurement module, and (iv) a thermoelectric generator integrated into the measurement module. Measurement station **91** contains at least one sensor for detecting a parameter of interest related to the integrity of pipeline **90**. Such parameters include, but are not limited to, (i) corrosion, (ii) pressure, (iii) temperature, (iv) fluid flow state, (v) vibration,

(vi) chemical composition,(vii) mechanical strain, (viii) chemical contamination, (ix) radioactive contamination, (x) biological contamination, (xi) inclination of the pipeline, and (xii) seismic events.

Sail **92** acts to intercept a portion of flow **96** for propelling interrogation device **86** along pipeline **90**. Sail **92** may be adjustable in size by adjusting supports **93** under command of controller **107**. Sail **92** may be of any suitable shape.

In operation, interrogation device **86** is propelled along the internal passage **88** of pipeline **90** at a predetermined speed as controlled by controller **107**. The obstruction to flow presented by interrogation device **86** creates a pressure differential **101** (see **Figure 9C**) that is imposed on pipeline **90**. The pressure differential **107** is related to the resistance to movement of interrogation device **86**. The pressure differential may be controlled by adjusting the braking resistance and/or the sail size. The pressure differential versus speed may be calibrated for a given configuration and a known gas, such as air, and correction factors may be used to predict performance for other gases, such as hydrocarbons. The pressure differential **101** moves essentially as a wave with interrogation device **86** and impresses a strain in pipeline **86** in the area proximate interrogation device **86**. Measurement stations **91** disposed along pipeline **90** may have sensors for measuring parameters of interest related to the strains in pipeline **90** as the pressure differential is imposed on the pipeline in the proximity of each measurement station. In one preferred embodiment, measurement station **91** contains sensors to measure the static pressure of the gas **96** flowing in pipeline **90**. In addition, measurement station **91** has at least one sensor for measuring such parameters of interest, for example, as (i) axial strain on the pipeline, (ii) circumferential strain, also called

hoop strain, on the pipeline, (iii) and acoustic emission from micro-fractures in the pipeline. Such strain gages may include mechanical strain gages and/or fiber optic strain gages. Such parameters are common indicators, known in the art, for indicating the integrity of a pipeline. For example, the strain measurements may be related to the combined stresses imposed on the pipeline by the pressure differential. Of particular interest would be changes in such readings over a period of time. Such changes in stresses could be indicative of metal loss due to corrosion and/or erosion. Changes in acoustic emissions from micro-fractures could be indicative of metal fatigue and/or crack growth, a major failure mechanism. Model relationships may be developed between the pressure differential and previously discussed parameters and such models, or relationships, monitored over time for the indicated changes. By transmitting the pressure information read by measurement station **91**, controller **107** may compare the actual measured differential pressure to the predicted differential pressure. If the difference is outside a predetermined limit programmed into the processor, the processor adjusts the sail size and/or braking to bring the pressure differential back within limits. Such data may be presented in graphical form for ease of interpretation.

In one preferred embodiment, interrogation device **86**, traverses pipeline **90** and interrogates each measurement station **91** as device **86** passes in proximity to each station **91**. Each measurement station may have a unique digital identifier included in each transmission to interrogation device **91**. The location of each measurement station along pipeline **90** is logged at installation of each measurement station. The use of the identifier for each station allows recalibration of the distance and speed indication of interrogation device **86** as it traverses between measurement stations **91** in pipeline **90**.

The foregoing description is directed to particular embodiments of the present invention for the purpose of illustration and explanation. It will be apparent, however, to one skilled in the art that many modifications and changes to the embodiments set forth above are possible. It is intended that the following claims be interpreted to embrace all such modifications and changes.